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Possibilities of recovery of fine-fraction energy waste from fluidized bed boilers in underground mining for liquidation of underground workings

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Abstract
Currently, the Polish power industry is mainly based on solid fuels, such as hard coal and lignite, and there is a problem with the management of significant amounts of combustion waste. One of the directions of recovery of these types of waste is underground hard coal mining operations, where the general problem of their management is the variability of physical and chemical properties resulting from the combustion of fuels of different parameters in power boilers with different exhaust gas cleaning solutions, mainly desulphurization methods. One of the solutions for energy production currently in use is the combustion of coal in fluidized bed boilers, in which the so-called dry desulfurization method is adopted. As a result of this process, a fine-fraction waste with the European code 10 01 82 is created, which is characterized by pozzolanic features, enabling its use wherever specific strength parameters are expected from the material. One such technology is the liquidation of underground workings based on the pouring of a hydro-mixture into the fenced-off space of the workings using a gravity-fed pipeline. The space to be filled is fenced off by closing it on both sides with dams, usually made of brick walls, located at an appropriate distance. It should be taken into account that the hydro-mixture will tend to slow the sedimentation of solid particles on the spreading path, and working may have a variable slope. The paper presents the results of laboratory tests of the physical and mechanical properties of hydro-mixtures made on the basis of selected energy waste from a fluidized bed boiler, along with a practical example of its application for the liquidation of underground workings.

Introduction

For many years, Polish hard coal mines have been using large amounts of waste materials, including fine-fraction energy waste in the form of hydro-mixtures in various underground mining technologies. These include the sealing of goafs, construction of dams, and filling plugs or liquidation of underground voids (Plewa & Kleta, 2001; Plewa & Mysłek, 2001; Plewa, Popczyk & Mysłek, (2007). The use of ash-water hydro-mixtures in underground mining is legally regulated by the ordinance of the Minister of the Environment (Regulation, 2015) issued with the Waste Law (Legal Act, 2012) and has the legal form of waste recovery. In addition, the required physical and mechanical properties of hydro-mixtures are defined in the standard PN-G/11011:1998, which is not binding but, due to the lack of other standard-specific regulations, is widely recommended and used in ore and hard coal mining. Currently, the energy waste market is dominated by such products since various fly ashes captured in electrostatic precipitators have the codes 10 01 02 and 10 01 82 (Popczyk, 2017a). The ashes with the code 10 01 02 are fly ashes from coal produced in conventional boilers without the desulphurization processes. Their use in underground mines, due to the lack of binding properties, is possible only in fire prevention for sealing goafs or filling sub-level workings and post-mining voids. In addition to mining, these types of waste are widely used in the construction industry to produce building elements, cement, and concrete.

According to the assumptions of the Polish government, the Polish hard coal mining industry is currently undergoing another phase of transformation that consists of a slow liquidation of the hard coal mining in Poland until the year 2049. The decommissioning process of a mining plant is, in practice, a very complex issue and includes, among others, the liquidation of underground workings, which in some justified cases requires, among others, tight filling of liquidated spaces. Considering the significant amount of underground workings intended to be liquidated by filling them in, it is reasonable that the filling material should be cheap and widely available. Due to the fact that the combustion of hard coal generates a significant amount of fine-fraction energy wastes obtained from electrostatic precipitators and various desulphurization methods installed in power plants, these wastes are commonly used in underground workings in various mining technologies, including the liquidation of underground workings. This technology is based on the introduction of a fine-fraction hydro-mixture into the fenced-off space of the underground excavation, which often has binding properties, using a gravity-fed pipeline system. An exemplary diagram of the technological process of using fine-fraction energy waste to liquidate underground workings is shown in Figure 1.

This solution is characterized by the fact that the mixing station for the preparation of hydro-mixture is built on the ground surface, which is not always close to the backfilling shaft or the opening into which it is fed. The energy waste delivered with road tankers is discharged pneumatically to the storage silos or directly into the mixer, which is also fed with water. The method of preparing the mixture with appropriate physical and mechanical parameters must be performed in an accurate and repeatable manner, i.e., the structure of the mixer must ensure a high mixing accuracy of the hydro-mixture with smooth adjustment of batching of the components. The installation is equipped with monitoring devices, such as flow meters, and a density gauge to regulate the batching process of components, which automatically respond to the readings of the density

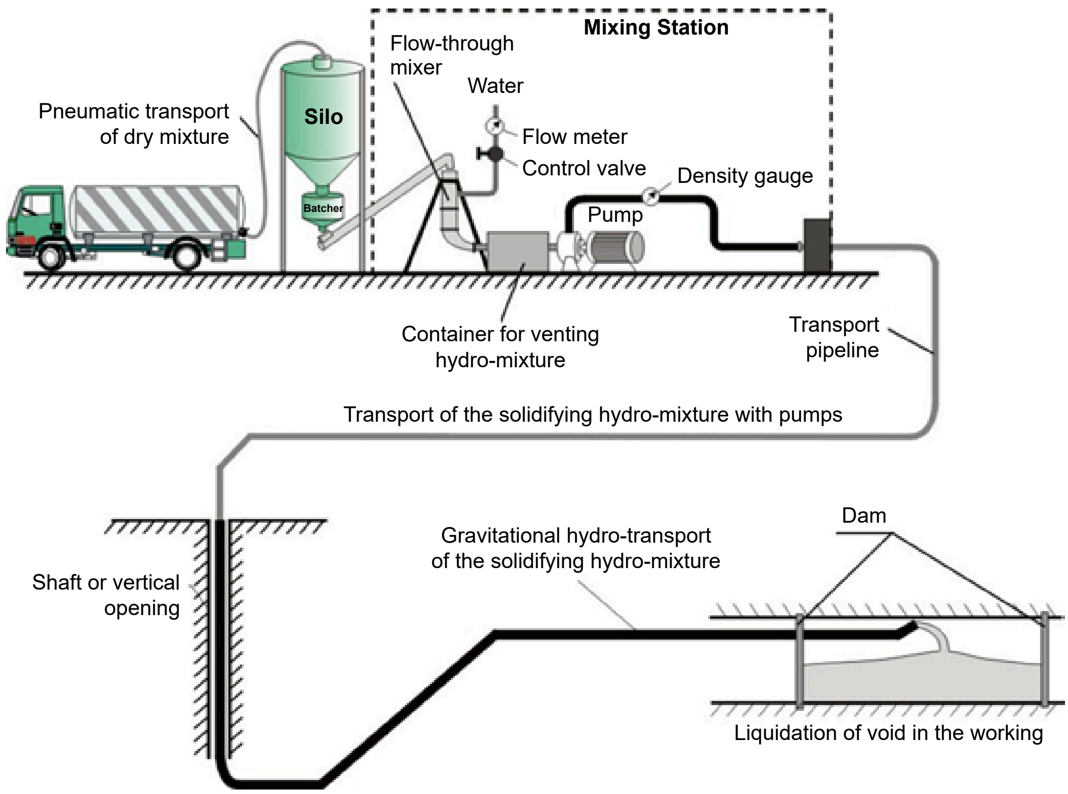

Figure 1. Diagram of the installation for the use of energy waste for liquidation of underground workings with the mixing unit placed on the surface

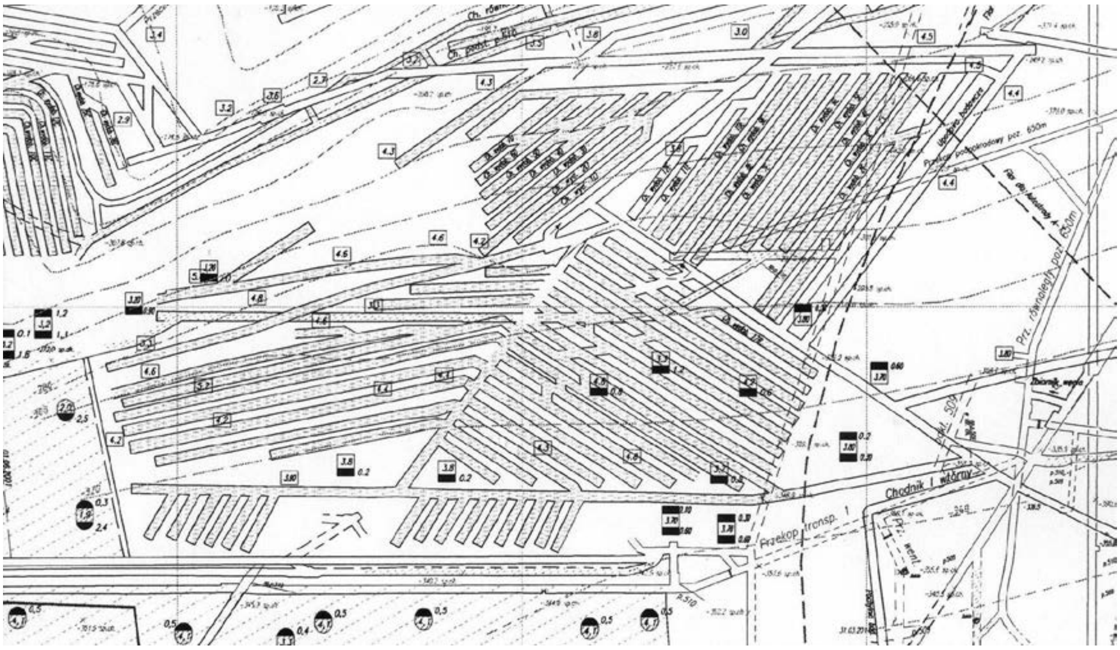

Figure 2. An example of coal seam mining with galleries and their liquidation by filling

gauge of the ready hydro-mixture. The installation is also equipped with a pump for forcing the finished hydro-mixture from the retention tank to the backfilling pipeline. This solution is characterized by a good preparation accuracy of the backfilling mixture, without an unnecessary amount of excess water, and it is recommended when the mixtures are used in technologies in which it is necessary to obtain appropriate values of rheological parameters, as well as subsequent strength parameters for the solidified hydro-mixture (Popczyk, 2018; 2020).

One of the backfilling examples of dog headings, created after hard coal mining operations, with ash-water mixtures is the exploitation of the seam with a thickness of approximately 4.0 m, as shown in Figure 2. The backfilled workings were bored with the use of AM-50 road headers, leaving pillars and solid coal between them with a width of 4 m to 6 m. The operating headings were designed to allow their maximum backfilling with hydro-mixtures and the outflow of excess water.

Formation and use of fluidized ashes

With respect to the fine-fraction energy wastes from the 10 01 82 group, the dominant group is composed of ash produced in the process of burning fine coal in fluidized bed boilers. Experience has shown that the resulting fluidized ashes are characterized by much improved pozzolanic properties compared to other ashes obtained from the method applied in fluidized bed boilers, referred to as so-called dry desulfurization in a fluidized bed (Popczyk, 2016). Currently, many boilers in the power industry use the so-called "fluidized combustion", and the ashes produced in them differ significantly in their physical and chemical properties, depending on the place of their formation.

Amid larger power plants located in the province of Silesia Voivodship, fluidized combustion is used, among others, in Power Plant "Jaworzno", "Siersza", or "Łagisza" and in Heat and Power Plant "Chorzów" or "Katowice". The main advantages of combustion in fluidized bed boilers include:

- the possibility of using sludge from coal enrichment installations as fuel,
- simple preparation of fuel for combustion and simple fuel supply to the combustion chamber,
- significant (80%) reduction of SO_2 emissions to the atmosphere by supplying sulfur-binding compounds to the deposit,
- low nitrogen dioxide emissions due to the low temperature of the deposit (850 ºC),
- high combustion efficiency due to turbulent mixing and the long residence time of particles in the circulation bed.

The main disadvantages of the fluidized bed combustion technology include:

- long start-up process from the cold state due to a large ceramic mass (6.5–7 h),
- much higher air pressure is needed for combustion compared to pulverized coal boilers, due to a higher flow resistance and the need to maintain a fluidized bed.

Ashes from fluidized bed boilers, due to their binding properties, are currently widely used for the production of mineral binders used, for example, in underground mining (Plewa, Popczyk & Piontek, 2009; Regulation, 2015). Such binders have guaranteed strength properties obtained by their stabilization resulting from the share of cement and enhancing additives. The use of such products in underground mines is justified when the specific technology requires the acquisition of sufficiently high and stable strength parameters in the position of their placements, such as an insulating plug, explosion-proof plug, or water dam. Otherwise, when the technology does not require stable high-strength parameters, it is possible to use hydro-mixtures made on the basis of ash from fluidized bed boilers only (Popczyk, 2021). An example of such an application is the use of ash-water hydro-mixtures for the liquidation of workings and underground voids. In this case, the ash-water hydro-mixtures should be characterized by (PN-G-11011:1998; Plewa & Kleta, 2001; Popczyk, 2017b):

- a significant range of spread,
- the smallest possible amount of seep (excess) water,
- binding and strength properties in a low range,
- resistance to soaking (action of groundwater).

From the point of view of the binding process and the final strength parameters, the proportion of water in the mixture should be optimized in terms of the effectiveness of the hydration process. However, because the mixtures are delivered hydraulically to the places of their application by means of gravity pipeline transport systems, the amount of water in the mixture is usually greater than when it results from the above-mentioned criteria, and it must consider the likelihood of such transport (Popczyk, 2017b). The optimization of the hydro-mixture composition must, therefore, account for both the previously mentioned requirements regarding the binding course and strength after solidification, as well as the needs regarding the flow conditions in the transport installation and the subsequent spread in the excavation.

Methodology and laboratory tests of hydro--mixtures on the basis of fluidal ashes

The tests of the hydro-mixtures, prepared on the basis of the selected wastes (coded as 10 01 82) in the form of fluidized ashes, were performed in the laboratory of the Department of Geoengineering and Raw Materials Exploitation in line with PN-G-11011. The research included the determination of the following selected parameters:

- S/W mass share (dry ash/water) and density,
- amount of excess water,
- compressive strength,
- soakability.

To show the variation in the physical and mechanical properties, which result from the different proportions of mixing water in the hydro-mixture with fluidized ash, laboratory tests of the hydro-mixtures were carried out for different S/W ratios (dry ash/water). To obtain the appropriate flowability of the mixture, which determines its physical properties, water was added to dry ashes in the amount necessary to obtain a specific consistency, defined by the standard of table spread of the mixture. To better visualize the differences in the tested parameters, depending on the proportion of water in the hydro-mixture, six different consistencies of hydro-mixtures were adopted, determined by the table spread parameter in accordance with PN-G-11011, with the values of 160, 180, 200, 220, 240, and 260 mm used.

The rise in the table spread of the mixture is achieved by increasing the proportion of water in the mixture. The effect of increasing the proportion of water is that the concentration of the solids is reduced, the density of the mixture is lessened, the viscosity is lowered, the binding time is extended, and the strength properties of the solidified mixture deteriorate; moreover, in an extreme case, it even results in the loss of its solidification capacity. Mixtures with the table spread below 200 mm are characterized by a more compact consistency, increased hydrotransport resistance, higher values of strength after solidification, and a smaller amount of excess water. From the viewpoint of hydrotransport, the mixture with a lower concentration of solids (table spread above 200 mm) ensures lower flow resistance in the installation and, hence, higher flow velocity and a greater range of hydrotransport. This is especially important in the case of a significant horizontal distance from the backfilling shaft to the work sites, or a small difference in levels between the ground surface and the position of the backfilling works. On the other hand, a mixture of high table spreads contains much more water than that which can be found by fly ashes contained therein. This water, known as over-sludge water, flows out of the place where the hydro-mixture is placed and merges with mine waters and may contribute to a possible increase in the water hazard. Taking the above into account, one should always attempt to optimize hydro-mixture composition in terms of the proportion of over-sludge water.

As mentioned earlier, in laboratory conditions, hydro-mixtures based on fluidized ash were made for six different proportions of ash-to-water mass, which provided hydro-mixtures with six table spread levels from 160 to 260 mm. After the hydro-mixtures had been prepared, the density and the amount of over-sludge water were determined; the results are summarized in Table 1. Simultaneously, samples were prepared from those hydro-mixtures for future strength tests.

Table 1. Designated selected physical properties of hydro-mixtures made on the basis of ash from a fluidized bed boiler

S/W proportions	Density [kg/m^3]	Table spread [mm]	Amount of over-sludge water [%]
1:0.75	1452	160	2.4
1:0.85	1434	180	4.2
1:1.00	1422	200	6.9
1:1.05	1411	220	9.1
1:1.12	1398	240	13.3
1:1.20	1386	260	16.2

As can be observed from the conducted research, along with the increase in the proportion of water in the composition of the mixture, its table spread increases and its density decreases. With a rise in the table spread in the range from 160 to 260 mm, the density of the mixtures decreased from 1452 to 1386 kg/m^3, while the S/W mass ratio increased from 0.75 to 1.20.

The amount of over-sludge water that flows out of the hydro-mixture, at the place where it is located, is in the range of 2.4 to 16.2%. The highest amount of over-sludge water (i.e., 16.2%) was contained in the hydro-mixture with the highest proportion of water and the highest table spread of 260 mm. The smallest amount of over-sludge water (i.e., 2.4%) was contained in the hydro-mixture with the smallest water content and the smallest table spread of 160 mm.

The tests of uniaxial compressive strength R_c of the hydro-mixtures, made on the basis of fluidized ash, were carried out after 7, 14, 28, and 60 days. To reproduce the typical climatic conditions in the underground workings of mines, the samples of the mixtures were seasoned in the LTB 650 RV climatic chamber made by Elbanton in the following storage conditions: temperature 25°C and humidity 95%. Additionally, after 60 days, the samples were soaked with water for 24 hours to determine their soakability, i.e., the degree of strength loss R_c. The results of those tests are summarized in Table 2 and Figure 3.

Table 2. Strength to uniaxial compression, and the slakeability of hydro-mixtures, prepared on the basis of selected fluidized ashes depending on their table spread

Table spread of hydro-mixture	Strength R_c [MPa]					Slakeability K [%]
	7 days	14 days	28 days	60 days	R_c 60 + 24 h of water soaking	
160	0.48	1.25	2.85	3.52	3.25	7.7
180	0.42	1.22	2.68	3.33	3.02	9.3
200	0.32	1.08	2.45	3.15	2.77	12.1
220	0.26	0.98	2.21	3.08	2.54	17.5
240	0.19	0.83	1.92	2.89	2.26	21.8
260	0.15	0.74	1.75	2.58	1.93	25.2

The resistance tests on uniaxial compression of samples made in laboratory conditions showed that, with an increase in the seasoning time in the climatic chamber, the R_c resistance grows. Additionally, it can also be seen that the resistance R_c decreases along with an increase in the table spread of the hydro-mixture. After seven days of seasoning in a climatic chamber, the resistance of the hydro-mixtures fell for the table spread range from 160 to 260 mm, since it dropped from 0.48 to 0.15 MPa, respectively. After 14 days, with the same spread table range, the R_c resistance decreased, ranging from 0.125 to 0.74 MPa. After 28 days, it was from 2.85 to 1.75 MPa and, after 60 days, it was from 3.52 to 1.93 MPa.

All tested samples, after 60 days of seasoning in a climatic chamber and 24 h soaking in water, showed a specific loss of R_c resistance. It was also noticed that, with the increasing table spread, the loss of resistance was greater. The lowest slakeability value of 7.7% was recorded for the hydro-mixture with a table spread of 160 mm, while the highest slakeability of 25.2% was found for a table spread of 260 mm.

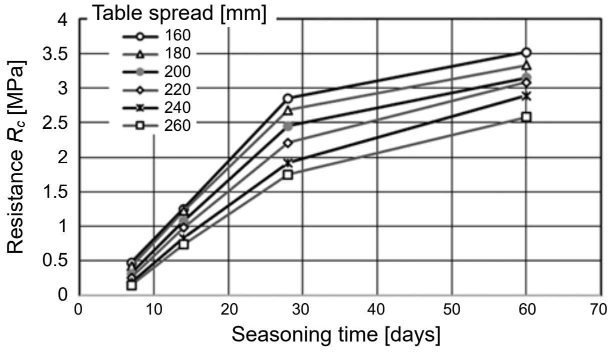

Figure 3. Resistance to uniaxial compression of hydro-mixtures over time, based on fluidized bed boiler ash for different table spreads

Liquidation of underground workings with fine-fraction hydro-mixtures

The liquidation of underground workings by their backfilling is mainly associated with the construction of dams with appropriate strength parameters and backfilling of the fenced-off space; thus, their creation is most often with binding mixtures. The construction of dams with an adequately durable structure is particularly important when filling the free space with hydro-mixtures made of waste materials, where it is difficult to lead the water away in contrast to backfilling materials (i.e., sand and stone), and they trigger a different course of pressure changes affecting the dam structure over time. This is becoming particularly important when filling the workings of extensive length and greater slope, which requires the so-called partial filling in stages. The separating or backfilling dams made in mines are significantly diversified in terms of construction, material consumption, and labor, which affects their strength properties. The methods of building these dams most often result from the traditions and experiences gathered by individual mines.

The load-bearing structures of the separating or backfilling dams may be loaded with the following:
- the hydrostatic pressure of the mixture,
- the dynamic pressure of the liquid mass,
- additional load resulting from adding waste material in the case of using wastes or their mixtures.

The fencing-off of the working excavation space, which is then backfilled with hydro-mixture, is made by damming the excavation on both sides with brick dams, usually made of concrete blocks on cement mortar, located at an appropriate, defined distance from each other. The basic problem is to determine the optimal distance between the dams from the viewpoint of expenditure, so that the liquidated space is completely filled, taking into account that the fed material will have a liquid-plastic consistency, and its feeding into the enclosed space will be performed at one point of discharge from the transport pipeline. It should also be considered that the feed mixture will tend to slow the sedimentation of solid particles on the flow path in the excavation, and the excavation may also have a variable slope. A pictorial drawing of the liquidation of the dog heading excavation by backfilling it is shown in Figure 4.

In this drawing, we can see the space separated by two dams, one of which is full and without holes (the rear dam), while the other front dam has several inspection openings and two pipelines. The pipeline feeding the hydro-mixture, and the venting pipeline for the filled space, are also shown. The inspection openings are placed on the vertical axis every 0.5 m. They are designed to inform about the rising level of the hydro-mixture sediment while filling the free space of the excavation; they also allow for the drainage of excess water.

The hydro-mixtures intended for the liquidation of underground workings must meet a number of

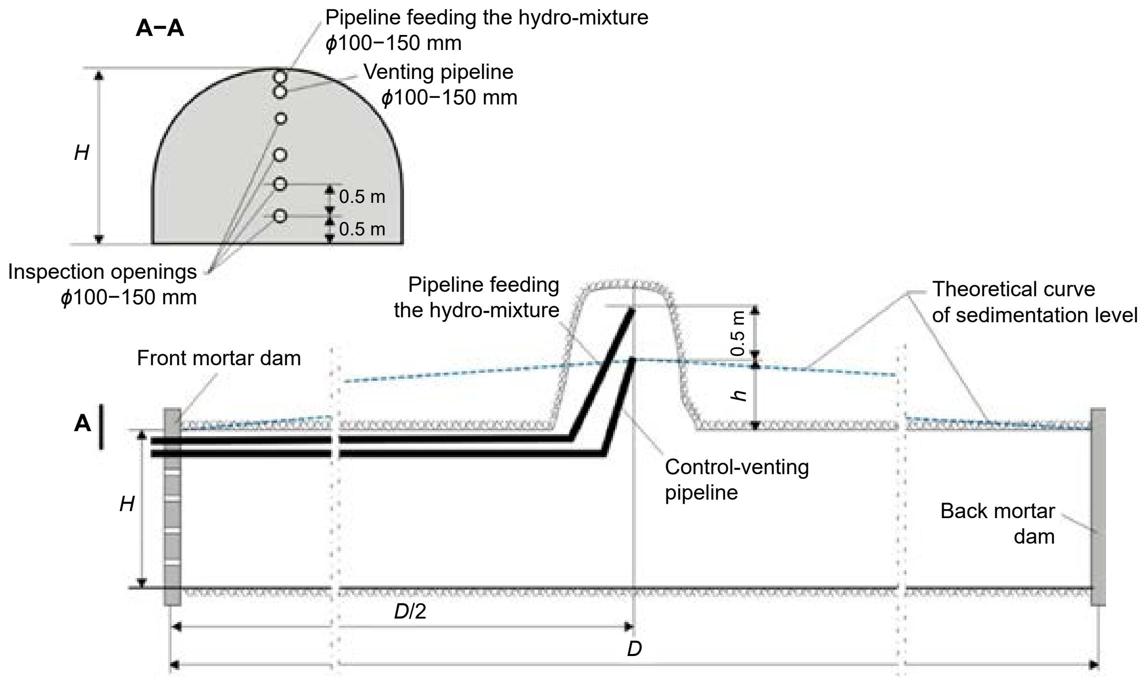

Figure 4. Diagram of the liquidation of a dog heading by a complete filling of the free space with a fine-fraction hydro-mixture

physical and mechanical criteria, in particular, the binding process and strength. To ensure the optimal course of the hydro-mixture binding process, and the strength parameters after its solidification, such hydro-mixtures are usually made of fly ash having binding properties with the possible participation of a binding agent, which is most often cement. From the point of view of the binding process and final strength parameters, the proportion of water in the mixture should be optimized in terms of the effectiveness of the hydration process and the chemical balance in the solidifying mixture. As the mixtures are delivered to their places of application, usually by hydraulic transport, the amount of water in the mixture is greater than that which results from the above-mentioned criteria, because it must take into account the parameters of hydraulic transport.

The optimization that involves the determination of the distance between the dams consists mainly of the assumption that, after considering the slope of the sediment surface (which can be determined at a laboratory stand), the working will be backfilled to the full height at the places were separating dams were placed. This assumption is possible in a horizontal working only in the case of feeding the hydro-mixture higher than the upper height of the working, as shown in Figure 4. In the central part of the liquidated space, it is necessary to extract some loose roof rocks, which makes it possible to raise the outlet of the pipeline supplying the hydro-mixture to a specific height *h*, and to ensure damming of the hydro-mixture. To guarantee that the adopted height *h* is attained, a venting and control pipeline is added. After the hydro-mixture reaches height *h*, the hydro-mixture will flow out through the control pipeline beyond the dam, which will indicate that the assumed height has been reached. Table 3 presents examples of the optimal distances between the mortared dams, for a hydro-mixture prepared on the basis of fluidized ash of the consistency measured with the table spread equal to 160 mm, determined on the basis of the model slope tests of the hydro-mixture sediment.

Table 3. Example of the optimal distance between the dams *D* [m] with the backfilling and a hydro-mixture based on the extracted fluidized ash with a table spread of 160 mm, depending on the height of the excavation and the over-height difference *h*

Height of the working *H* [m]	Degree of overheight, *h* [m]					
	0.25	0.50	0.75	1.00	1.25	1.50
2.2	10.88	19.74	27.10	33.32	38.62	43.22
2.3	10.92	19.90	27.40	33.76	39.22	43.98
2.5	11.00	20.16	27.92	34.58	40.34	45.38
2.6	11.06	20.32	28.20	35.00	40.90	46.10
2.7	11.08	20.44	28.44	35.36	41.40	46.72
2.8	11.12	20.54	28.64	35.68	41.86	47.30
3.0	11.16	20.74	29.04	36.30	42.70	48.40
3.2	11.24	20.94	29.44	36.90	43.54	49.46

Conclusions

Polish underground coal mines commonly use various fine-fraction energy wastes, which differ significantly in terms of their physical properties. These differences mean that the hydro-mixtures made with the same mass fractions of solids-to-water (e.g., 1:1) are characterized by significantly different physical properties, such as their table spreads, amount of excess water, unit energy losses of the flow, rheological parameters, or strength parameters. Considering the above, when undertaking any work involving the use of this type of hydro-mixtures, it is necessary to perform preliminary laboratory tests to determine its physical properties for a specific kind of energy waste. This fact is often forgotten in mines, and to ensure the so-called "safety" of pipeline operation of the transport installation, much larger amounts of water are added than would appear from the tests and requirements. This results in an increased share of excess water, which in turn has to be pumped out to the surface, in the leakage of the diluted hydro-mixture to the fracture zones of the rock mass and in the failure to achieve the required strength parameters.

This paper presents the results of research on the selected physical and mechanical properties of a solidifying hydro-mixture made on the basis of selected energy wastes in the form of ashes from a fluidized bed boiler. In the laboratory tests, hydro-mixtures made based on selected fluidized ash were used, with different mass fractions of the ash-to-water S/W, which resulted in the acquisition of various consistencies of the hydro-mixture and, consequently, different table spreads. This made it possible to show the influence of the water content in the hydro-mixture on the strength parameters, and a later estimation possibility for the consistency of the hydro-mixture introduced into the excavation, based on the obtained results of in-situ strength tests. For laboratory tests, the table test range of hydro-mixtures was assumed to be from 160 to 260 mm.

Based on the obtained results of the laboratory tests of the hydro-mixtures using the selected ash from the fluidized bed boiler, presented in point 2 of the paper, the following conclusions can be drawn:

- with the increase in the proportion of water in the hydro-mixture, its density decreases. In the range of the table spread from 160 to 260 mm, the density was from 1452 to 1386 kg/m^3, respectively;
- along with the increase in water content in the hydro-mixture, the amount of over-sludge water grows. In the table spread range from 160 to 260 mm, this amount was from 2.4 to 16.2%, respectively;
- with increased water content in the hydro-mixture, the uniaxial compression strength R_c decreases. As shown in Table 3, after 28 days of seasoning, the table spread ranged from 160 to 260 mm, the strength drops from 2.85 to 1.75 MPa and after 60 days from 3.52 to 2.58 MPa;
- all tested samples, after 60 days of seasoning in a climatic chamber and 24 h soaking in water, showed a loss of strength. The lowest soakability value of 7.7% was recorded for the hydro-mixture with a table spread of 160 mm, while the highest soakability of 25.2% was seen for a table spread of 260 mm.

Taking into account the technology of filling, using a cyclical gravity flow with the hydro-mixture acting down the workings, the obtained test results confirmed that the hydro-mixture should be characterized by higher table spread properties for increasing the migration range and attaining complete filling. It should be remembered that, with a table spread of 240 mm, the hydro-mixture has about 21.8% of over-sludge water (Table 3). Before introducing the hydro-mixture in the next cycle, this water should be pumped off or drained with the drainage pipes left behind. Otherwise, the water left in the excavation will combine with the new hydro-mixture and dilute it, resulting in a lower strength. In extreme cases, it is possible to feed fine-fraction hydro-mixture into the water while liquidating waterlogged workings or shafts. In such a case, comparative laboratory tests should be performed, which attempt to reproduce similar dosing and seasoning conditions of hydro-mixtures to confirm their suitability.

The research results presented in the paper enable us to conclude that the applied hydro-mixtures, based on fluidized ash, can be successfully recommended for all liquidation and filling works in underground workings. The undeniable advantage of these hydro-mixtures is the achievement of high R_c strengths without the addition of binders, which makes them a substitute for the used mining binders in the strength class up to 3 MPa.

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